Received: 27 August 2020 | Revised: 23 December 2020 | Accepted: 28 December 2020

DOI: 10.1002/dep2.136

ORIGINAL RESEARCH ARTICLE

The Depositional Record Open Access
A journal of the International Association of Sedimentologists
WILEY

# Effects of salinity, organic acids and alkalinity on the growth of calcite spherulites: Implications for evaporitic lacustrine sedimentation

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**Funding information**
Origin Center, project 190438131, Dutch Research Council (NWO) and Dutch National Science Agenda (NWA), Grant/Award Number: 190438131

## Abstract

Lacustrine non-skeletal carbonates exhibit a diversity of petrographies due to interactions between physico-chemical and biologically influenced mechanisms. Despite the suggestion that evaporative concentration was involved in the formation of spherulite and shrubby-bearing carbonate successions in the Pre-Salt Cretaceous alkaline lakes of the South Atlantic, no consensus exists about the water chemistries promoting these exotic mineral textures. In this work, an experimental approach was developed to evaluate how changes in salinity (NaCl) and biopolymer concentrations (alginic acid) impact calcite growth dynamics from saline and alkaline synthetic solutions. Hydrochemical and petrographical data from selected modern saline/alkaline environments were compared with experimental datasets to further estimate how the underlying (bio)chemical conditions and lake locations probably converge to allow the formation of calcite spherulite grains in evaporitic settings. Spherulitic calcite from Recent saline lakes and experiments arise from waters with moderate to high [Calcium]/[Alkalinity] ratios ([Ca]/[Alk]) rather than in calcium-depleted and alkaline-rich environments which tend to produce single-crystal calcites during abiotic water mixing or lake evaporation. This observation is consistent with the assembly of polycrystalline textures being a kinetically controlled feature, forced by remarkably high rates of nucleation. Also, the data analysed do not support a causative relationship between evaporite-driven salinity fluctuations and the preferential formation of spherulites, shrubs or their intermediate textures. Ubiquitous in saline lakes, organic substances can lower the kinetic thresholds for spherulitic calcite aggregation while microbial photosynthesis can also raise pH, altogether enhancing calcite supersaturation and promoting spherulite formation in waters with moderate-high [Ca]/[Alk] ratios and high salinities. Localised observations of abiotic spherulites in Recent soda lakes can occur in restricted mixing zones where [Ca]/[Alk] ratios are enhanced. This work highlights the roles of concentration regimes associated with biopolymers and microbial metabolism against the background salinity fluctuations in determining the morphological and textural transitions in lacustrine carbonate minerals.

**KEYWORDS**
alginic acid, alkaline, calcite, evaporation, salinity, shrub, spherulite

## 1 | INTRODUCTION

One of the longstanding conundrums in sedimentology lies in how to demarcate the influences exerted by abiotic processes and biologically influenced mechanisms in the formation and early diagenesis of non-skeletal carbonates (Bosak et al., 2004; Brasier et al., 2015; Capezzuoli et al., 2014; Fouke, 2011; Kelts & Talbot, 1990; McLoughlin et al, 2007; Morse et al., 2007; Rainey & Jones, 2009; Sánchez-Navas et al., 2013; Sánchez-Román et al., 2008, 2011; Serebryakov, 1976; Stalport et al., 2005; Wacey, 2010; Webb, 1996; Wilkinson & Given, 1986; Wright, 2012). It is still necessary to unify criteria to evaluate whether non-enzymatic carbonates have a biogenic influence, or whether they can form totally abiotically. This problem remains one of the most fundamental in sedimentology, critically conditioning models of how life has impacted substrate formation, lithification and diagenesis on Earth (Hodgson et al., 2018). Moreover, this issue permeates through the recognition of early life signatures on Earth and in the solar system (Brasier et al, 2015; Chan et al., 2019).

On Earth, continental environments form incredibly diverse associations of micron-sized carbonate crystals comprising different mineralogies and fabrics (Capezzuoli et al., 2014; Frisia et al., 2000; Jones, 1994, 2017; Jones & Peng, 2014; Jones & Renaut, 1995; Pedley et al., 2009; Sánchez-Román et al., 2009; Sanz-Montero et al., 2019; Taylor & Chafetz, 2004), thus representing excellent sites to evaluate whether crystal morphogenesis arises from physical, chemical or biological processes or a combination of them.

More recently, this debate has focussed on the origin of some enigmatic but abundant carbonate textures forming the Cretaceous Pre-Salt hydrocarbon reservoirs of the South Atlantic margins (Gomes et al., 2020; Luiz-Dias, 2005; Mercedes-Martín et al., 2016, 2019; Muniz & Bosence, 2015; Terra et al., 2010; Wright, 2012; Figure 1A,B). These carbonates have been described as constituted by the recurrent combination of two morphological end-members: fibro-radial polycrystalline calcite spherulites and upward bifurcating and dense radiating, fibrous to bladed, fascicular-optic to radial-fibrous, polycrystalline shrubs (Farias et al., 2019; Gomes et al., 2020; Herlinger et al., 2017; Saller et al., 2016; Terra et al., 2010; Wright & Barnett, 2015; Figure 1A,B).

The close association of these carbonates with authigenic Mg-rich clays such as stevensite, talc or kerolite, the scarcity of voluminous sulphate deposits and the apparent lack of marine fossils have been interpreted as indicative of highly evaporitic settings commonly associated with saline lacustrine environments (Farias et al., 2019; Lima & Ros, 2019; Saller et al., 2016; Tosca & Wright, 2015; Wright & Barnett, 2015). Mineral assemblages found in these lakes strongly advocate for alkaline environments with elevated pH, Mg/Si ratios as well as salinity (Tosca & Masterson, 2014; Tosca & Wright, 2015; Tutolo & Tosca, 2018). The interpretation that Mg-silicate precipitation arose from evaporative concentration over extensive lacustrine areas (Darragi & Tardy, 1987; Deocampo & Renaut, 2016; Jones, 1986) has favoured the view that Pre-Salt minerals formed in waters containing only modest concentrations of $Ca^{2+}$ and $Mg^{2+}$ ions while being net alkaline systems with initial $[Ca^{2+}]/[CO_3^{2-} + HCO_3^{2-}]$ ratios less than 0.5 (Tutolo & Tosca, 2018). However, although such voluminous polycrystalline carbonate formations are probably unique, materials with these polycrystalline characteristics are not rare, being found in a range of terrestrial environments (Chaftez et al, 2018; Erthal et al., 2017). These terrestrial settings generally exhibit biological influence on precipitation and occur in calcium-rich systems fed by meteoric waters. Spherulites very comparable to the Pre-Salt are reported from hyperalkaline springs with high calcium concentrations, where they contact with the atmosphere consuming large masses of $CO_{2(g)}$ enabling extensive carbonate-clay-silica precipitation (Chavagnac et al., 2013; Rogerson et al., 2017).

Earlier models interpreted the Pre-Salt lacustrine mineral morphologies and facies successions as generated by successive cycles of lake evaporation and refilling (Wright & Barnett, 2015), prompting specific 'chemical divides' (sensu Eugster & Hardie, 1978) and allowing critical mineral precipitation events. According to Wright and Barnett (2015), the progressive evaporation of lake waters promoted the successive formation of authigenic Mg-clays, followed by spherulite growth within clay gels, and finally the development of crystal dendrite shrubs in areas of reduced clay presence (Wright & Barnett, 2015; Wright & Tosca, 2016; Figure 1C,D). An alternative evaporitic model by Farias et al. (2019), also based on the chemical divides of Eugster and Hardie (1978), suggested the following facies patterns: (a) formation of calcite shrubs associated with evaporative concentration stages in flooded lake areas, and (b) subsequent calcite spherulite and Mg-rich clay deposition, generated displacively within the unconsolidated muddy sediment during desiccation stages.

Models by Wright and Tosca (2016) imply that increased evaporation is followed by the preferential formation of shrubs over spherulites, while Farias et al. (2019) determined that under similar conditions spherulites are formed rather than shrubs. These models assume that lacustrine carbonate precipitation is an abiotic and thermodynamically forced

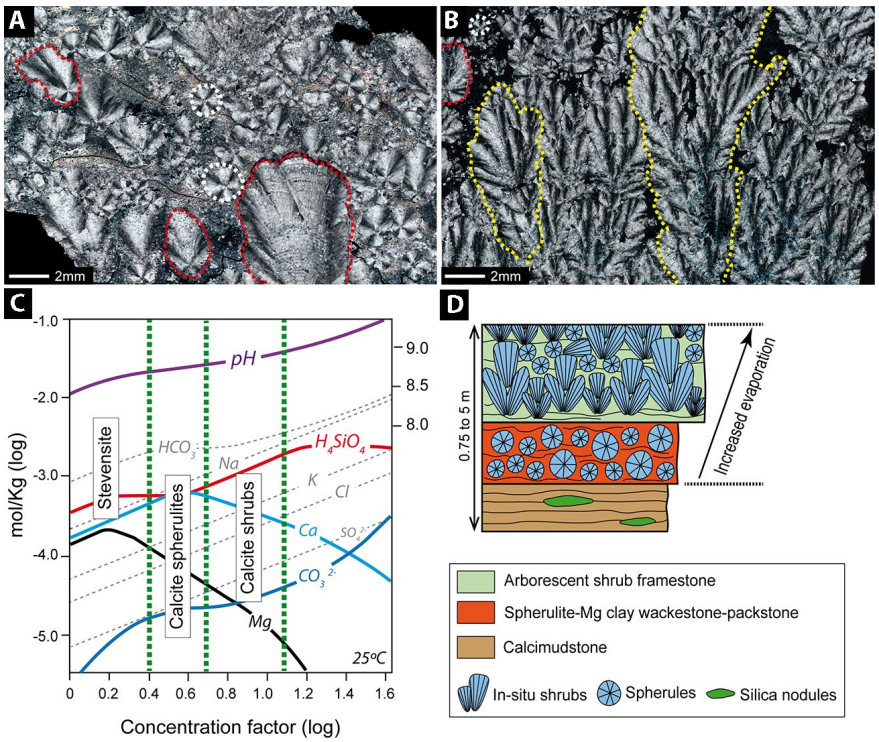


**FIGURE 1** (A, B) Spherulitic carbonates recognised in Aptian Pre-Salt lacustrine settings. Fibro-radial polycrystalline calcite spherulites (white lines), and vertical and upward bifurcating, fascicular-optic to radial-fibrous, polycrystalline shrubs (yellow lines) coexisting with intermediate forms (red lines) (courtesy J. Gomes, Petrobras). (C) Previous thermodynamic model used to explain transitions between Pre-Salt minerals (green lines) as related to the water concentration factor in shallow evaporitic lakes (Wright & Tosca, 2016). Note that Na and Cl concentrations increase during evaporation. Despite the initial increase in both $CO_3$ and Ca contents (stevensite zone), and $CO_3$ continuing to rise while Ca drops (calcite zone), the calcite solubility product remains broadly constant across the entire evaporative trajectory given that mineral precipitation is in equilibrium. (D) Facies successions proposed for the Pre-Salt sediments as a result of increased evaporation (Wright & Barnett, 2015; Wright & Tosca, 2016)

process triggered by evaporative-induced chemical divides (Figure 1C,D). As illustrated in their thermodynamic model (Figure 1C), Wright and Tosca (2016) assume that calcite/stevensite precipitation takes place in equilibrium during the evaporation trajectory while a progressive rise in sodium and chloride solute concentrations occurs (see Figure 1C). However, this model overlooks a finding of crystal engineering research that polycrystalline precipitation reflects kinetic rather than thermodynamic forcing (Sunagawa, 2005), and the repeated observation that the millimetre-sized spherulites developing today are associated with biological influences (Bischoff et al., 2020; Chafetz et al., 2018).

The absence of Recent alkaline saline lakes precipitating quantitatively abundant spherulite-shrub facies prevents a detailed evaluation of the intricate biotic-influenced/abiotic parameters involved in the formation of these carbonates. This conundrum undermines the ability to delineate the parameter space and depositional processes governing the formation of intermediate morphologies between spherulites and shrubs (Figure 1A,B; Gomes et al., 2020). Thus, this question reflects a serious knowledge gap in understanding the origin and diagenesis of lacustrine carbonates in alkaline, saline settings.

The purpose of the present work is to investigate the conditions promoting or inhibiting calcite spherulite and shrub formation by comparing laboratory observations with data from alkaline saline lakes, following a heuristic methodology. Comparisons between hydrochemical data from Recent spherulite-producing alkaline and/or saline lakes, with data from lakes that are not known to precipitate spherulitic carbonates were made with the purpose of relating petrography with lake water chemistry. In addition, an experimental set-up was designed to test whether calcite spherulite growth morphology could be altered by salinity fluctuations driven by evaporative concentration. To this end, the effects of increased evaporation (i.e. rise in sodium and chloride in solution) were simulated while keeping other variables essentially constant (i.e. calcite saturation index and [Calcium]/[Alkalinity] in solution; Figure 1C). By combining hydrochemical data from the natural lacustrine systems and laboratory scale experiments, it is possible to explore and discuss the links between salinity, [Calcium]/[Alkalinity] and organic acids (indicative of microbial metabolism) in the formation of calcite spherulites and shrubby calcite in lacustrine evaporitic settings.

# 2 | METHODS AND MATERIALS

## 2.1 | Parental batch preparation

Parental solutions were synthetically prepared to be comparable in terms of alkalinity to Mono Lake waters (Connell & Dreiss, 1995), a saline, alkaline lake system located in Sierra Nevada (California) (Table S1). All experiments were prepared in a stainless steel horizontal laminar flow cabinet equipped with a UV-C lamp to prevent external contamination. The parental solution was prepared by adding powdered/pearl reagent-grade anhydrous $Ca(OH)_2$, together with NaCl, $Mg(OH)_2$, $Na_2SiO_3$ and $H_3BO_3$ to deionised water (18 MΩ-cm). In order to investigate the effects of salinity and evaporative gradients, two types of parental solutions were prepared: a low salinity solution with 2.08 g/L NaCl (experiments 1 and 2) and a high salinity solution with 10.40 g/L of NaCl (experiments 3 and 4; Tables S1 and S2). In all experiments, a soda stream mechanism was used to bubble equal amounts of $CO_2$ into the parental solutions. To achieve sterility, powdered chemicals, frosted glass slides, tweezers and glassware were heat-sterilised by autoclave at 160°C for 2 hr. Deionised water was then autoclaved in an ASTELL Sterilizer at a maximum of 121°C and 1,700 millibars for 2 hr. Items that could not be heat-sterilised, such as tubing and plastic pipette tips, were treated with 16% hydrogen peroxide solution overnight.

## 2.2 | Experimental set-up of alkaline synthetic waters

The pH values of the parental solutions were subsequently adjusted to 12 by the addition of NaOH pellets. Once the targeted pH was confirmed using a glass-bodied Jenway 3510 pH meter electrode, aliquots were redistributed and essayed in 100 ml conical glass flasks (four flasks per experiment) which contained sterilised 1 $cm^2$ frosted glass slides. The flask filling process was carried out using sterile 0.22 μm diameter MF-Millipore filters to remove any contaminant particulates or pre-existing crystals which could have formed in the parental solutions. Initial alkalinities were systematically measured using a Mettler-Toledo T50 digital titrator and a DGi117-water pH electrode with a Rondolino autosampler (Table 1 and Table S2). After this stage, only experiments 2 and 4 were filled with 1 mg/L of sterile alginic acid, a common organic molecule from microbial cell walls. After alkalinity measurements, all the flasks from experiments 1–4 were sealed and agitated in an orbital flask shaker at 125 rpm. Continuous agitation ensures mixing of reactants while the experiments ran for 3 days at room temperature (about 25°C) in a controlled environment cabinet under dark conditions.

## 2.3 | Sampling and microscopic observations

After 3 days the solutions and precipitates were sampled. Frosted slides were oven-autoclaved at 100°C for 1 hr. Crystals precipitated in the bottom of the flasks were collected using a Büchner glass funnel with integrated sterilised cellulose nitrate filters (0.2 μm), which were autoclaved at 45°C for 1 hr. Frosted slides were removed from the flasks by using sterilised tweezers. Dried slides and friable material were placed on aluminium stubs, carbon coated and observed with a Zeiss EVO60 and JEOL J-7100F scanning electron microscope (SEM). The SEM imaging and measurements were performed at beam currents of *ca* 40 μA and *ca* 20 kV EHT accelerating voltage. Elemental X-ray analyses were also conducted with an Inca System350 Energy Dispersive X-ray Spectrometer (EDX). X-ray powder diffraction data were collected from the glass slides with crumbly material mounted in stainless steel sample holders. Measurements were performed between 20 and 50° (2Θ range) on solids. A PANalytical Empyrean diffractometer operating in Bragg–Brentano geometry with copper $K\alpha_1$ ($\lambda = 1.540546$ Å) and a PIXEL detector was used for data collection.

Elemental (Ca, Mg and Na) concentrations were measured using a Perkin Elmer Optima 5300DV inductively coupled optical emission spectrometer (ICP-OES). Selection of the analytical lines was based on the Perkin Elmer recommendations for the Optima 5300DV spectrometer: 393.366 nm for calcium, 280.271 nm for magnesium, and 589.562 nm for sodium. Calibration standards were prepared using 1,000 ppm standard stock solutions (99.9% pure or greater, PrimAg, Xtra, Romil) of calcium and magnesium. Samples were diluted with 5% ultrapure $HNO_3$ to bring the expected concentrations within or near to the linear calibration of the standards. Saturation indexes (SI) of calcite and sepiolite, solution ionic strengths, $[Ca^{2+}]$ and $[CO_3^{2-}]$ activities and $[Ca^{2+}]/[CO_3^{2-}]$ ratios of the initial and final solutions were calculated using the geochemical software PHREEQC (Parkhurst & Appelo, 2013). Furthermore, calcium and magnesium average removal rates from solutions were estimated (Table S2).

## 2.4 | Compilation of hydrochemical data from Recent saline lakes and experiments

A literature review on six Recent saline lakes/lagoons was carried out to analyse the potential links between salinity, [Calcium]/[Alkalinity] ratios (expressed as [Ca]/[Alk]), metal ion concentrations, and the carbonate products observed, either in the form of water column precipitates, loose sediments or benthic microbial-related deposits (Table 1). Lakes were selected on the basis of the previously

**TABLE 1** Summary of the hydrochemical and petrographical data from the studied saline, alkaline lakes and experimental datasets (including experiments herein). Source list on the right refers to petrographic data from naturally occurring sites

| | | | | | | | | | | | | | | Summary carbonate products | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Case study** | **Reference** | **Region** | **Sample source** | **Hydrological features** | **pH** | **Salinity (g/L)** | **Alkalinity (mEq/L)** | **Ca (mEq/L)** | **Mg (mEq/L)** | **Mg/Ca** | **Ca/Alk** | **Ca + Mg/Alk** | **Hydrochemical group** | **Sediments** | **Benthic microbial textures/deposits** | **References** |
| Lake Van | Reimer et al. (2009) | Eastern Anatolia (Turkey) | 5 m depth (1989) | Endorheic, saline, alkaline lake | 9.73 | 27.43 | 151 | 0.210 | 8.80 | 42.0 | 0.001 | 0.06 | Group 1 | Carbonaceous clayey silt | Microbialite chimneys | McCormack et al. (2019) |
| | Schweizer (1975) | | — | | 9.60 | 28.08 | 164.2 | 0.190 | 7.16 | 37.8 | 0.001 | 0.04 | | | | Stockhecke et al. (2014) |
| | Irion (1973) | | — | | 9.90 | 26.87 | 155.2 | 0.074 | 9.88 | 133.8 | 0.0005 | 0.06 | | | | Kempe et al. (1991) |
| Lake Clifton | Moore (1987) | Yalgorup lakes (Australia) | S1, fig. 8A, table 2, F12 | Coastal, hyposaline lagoon | — | 16.83 | 1.71 | 18.999 | 101.81 | 5.4 | 11.111 | 70.65 | Group 4 | Peloids, Micrite mud | Thrombolites | Burne et al. (2014) |
| | Moore (1993) | | T3 (0 m depth) | | 8.96 | 70 | 2.599 | 13.658 | 62.57 | 4.6 | 5.255 | 29.33 | | Skeletal sands | | Moore (1993) |
| Great Salt Lake | Domagalski et al. (1989) | Bonneville Basin, Utah (USA) | GSL3 transect (0, 15 m depth) | Endorheic, hypersaline lake | 8.5 | 84.34 | 6.5 | 5.988 | 14.98 | 2.5 | 0.921 | 3.23 | Group 3 | Ooids, oncoids | Thrombolites | Chidsey et al. (2015) |
| | Jones et al. (2009) | | Gilbert bay (1 m depth) | | — | 221 | 7.6 | 9.431 | — | 0.0 | 1.241 | 1.24 | | Peloids | Stromatolites | Della Porta (2015) |
| | Della Porta (2015) | | Bridge Bay/ North Arm | | 8.4 | 270 | 8.4 | — | — | — | — | — | | Micrite mud | Microbial peloidal cements | Vennin et al. (2019) |
| | Hahl et al. (1965) | | Measured in 1959–1960 | | — | 490.64 | 5.35 | 15.918 | 662.52 | 41.6 | 2.975 | 126.81 | | Microbial pustular grains ('pop corn') | Capping microbial crusts | Bouton et al. (2019) |
| Mono Lake | Newton (1994) | Mono Basin, California (USA) | Mono 1980 | Endorheic, saline, alkaline lake | 9.7 | 87 | 196 | 0.165 | 2.55 | 15.5 | 0.001 | 0.0139 | Group 1 | Micron-sized aragonite flakes | Carbonate mounds and pinnacles | Newton, 1994) |
| | Domagolski et al. (1989) | | Depth: 1 m | | 9.5 | 92.72 | 630 | 0.514 | 3.20 | 6.2 | 0.001 | 0.0059 | | | Clotted peloidal micrite | Connell and Dreiss (1995); Della Porta (2015) |
| | Connel and Dreiss (1995) | | MLK, 1992 | | 9.8 | 113.93 | 414.6 | 0.185 | 3.05 | 16.5 | 0.0004 | 0.0078 | | | | Brasier et al. (2018) |

(Continues)

**TABLE 1** (Continued)

| Case study | Reference | Region | Sample source | Hydrological features | pH | Salinity (g/L) | Alkalinity (mEq/L) | Ca (mEq/L) | Mg (mEq/L) | Mg/Ca | Ca/Alk | Ca + Mg/Alk | Hydrochemical group | Summary carbonate products | | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | Sediments | Benthic microbial textures/deposits | |
| Kiritimati | Arp et al. (2012) | Atoll of Kiritimati, Republic of Kiritibati (Central Pacific) | Lake 21 surface | Fresh to hypersaline | 8.37 | 201.8 | 4.24 | 75.848 | 394.88 | 5.2 | 17.889 | 111.02 | Group 4 | Microbialite intraclasts | Reticulate microbialites | Arp et al. (2012) |
| | | | Lake 21 porewater | Atoll lagoon-lake | 7.16 | 187.5 | 4.25 | 71.357 | 349.78 | 4.9 | 16.790 | 99.09 | | Loose spherulite sands | Microbial mat-related spherules | |
| | | | Lake 2 | | 7.95 | 170.82 | 3.64 | 76.846 | 324.26 | 4.2 | 21.112 | 110.19 | | | | |
| Rottnest | Bischoff et al. (2020) | Serpentine Lake (Western Australia) | October 2018, lake | Hypersaline lake | 8.10 | 312.5 | 2.6 | 38.600 | 528 | 13.7 | 14.846 | 217.92 | | — | Spherulitic microbialite | Bischoff et al. (2020) |
| | | | October 2019, lake | | 7.83 | 373.58 | 2.9 | 47.800 | 617.8 | 12.9 | 16.483 | 229.52 | | | | |
| Experiments | Tutolo and Tosca (2018) | — | | | | | | | | | | | | Summary crystal types | | |
| | | | Run B | Saline alkaline | 10.13 | 27.81 | 112 | 0.001 | 0.0004 | 0.3 | 0.00001 | 0.00001 | Group 1 | Dodecahedron-like single crystals | | |
| | | | Run E | Synthetic solution | 10.14 | 30.13 | 112 | 0.002 | 0.0206 | 11.1 | 0.00002 | 0.0002 | | Elongated dipyramid single crystals | | |
| | | | Run F | | 10.14 | 30.13 | 112 | 0.0002 | 0.0100 | 50.1 | 0.000002 | 0.0001 | | Protruded dipyramid, and rhombic single crystals | | |
| Experiments herein | Experiments herein | — | Experiment 1 | | 12 | 2.08 | 127 | 17.515 | 17.151 | 1.0 | 0.138 | 0.27 | Group 2 | Polycrystalline, fibro-radial spherulites | | |
| | | | Experiment 2 | Saline alkaline | 12 | 2.08 | 127 | 17.515 | 17.151 | 1.0 | 0.138 | 0.27 | | Polycrystalline, fibro-radial spherulites | | |
| | | | Experiment 3 | Synthetic solution | 12 | 10.40 | 131 | 17.515 | 17.151 | 1.0 | 0.134 | 0.26 | | Polycrystalline, fibro-radial spherulites and dumbbell-shaped spherulites | | |
| | | | Experiment 4 | | 12 | 10.40 | 131 | 17.515 | 17.151 | 1.0 | 0.134 | 0.26 | | Rhombic single crystals | | |
| Experiments | Beck and Andreassen (2010) | — | Experiment 13 | Saline, alkaline Synthetic solution | 7 | 53.87 | 37.42 | 529.79 | 0.00 | 0.0 | 14.16 | 14.16 | Group 4 | Polycrystalline calcite spherulites | | |
| Experiments | Tracy et al., (1998a) | — | Trial 8 | Saline alkaline | 8.2 | — | 36.7 | 99.99 | 100.02 | 1.0 | 2.72 | 5.45 | Group 2 | Polycrystalline, fibro-radial calcite spherulites | | |
| | | | Trial 16 | Synthetic solution | 8.2 | 0.7089 | 14.12 | 20.00 | 100.02 | 5.0 | 1.42 | 8.50 | | | | |

documented occurrence of spherulite calcite grains or polycrystalline calcite textures that could plausibly have formed contemporaneously with recent lake waters (Kiritimati atoll lake, Rottnest lagoon or Great Salt Lake). Comparisons were also made with other saline lakes/lagoons where such textures are unknown (Mono Lake, Lake Van and Lake Clifton). Values of salinity (g/L); alkalinity (mEq/L); pH; Mg/Ca ratio; calcium and magnesium concentrations (mEq/L); and [Ca]/[Alkalinity] ratios were gathered from the available literature when possible. Measurements come from surficial lake/lagoon water locations if not stated otherwise. Salinity is referred to the sum of [Na] and/or [Cl] concentrations either measured in the waters or calculated using PHREEQC geochemical software (Parkhurst & Appelo, 2013).

Limitations exist when relating lake water chemistry with Recent carbonate microfabrics and additional parameters including DOC, sulphate, phosphate or trace element concentrations may influence carbonate precipitation and morphology. Also, the chemistry of the lake sediment–water interface can differ from that of the water column. However, all of these influences would also cause deviation from a simple evaporation-forced scenario, and so do not undermine the evaluation. By comparing data from experiments and saline lakes, certain chemical scenarios emerge more favourable to the development of specific carbonate microfabrics than others. To ensure that the dataset was representative, samples from a range of hydrological settings were included. Hydrochemical data from previous experimental works addressing spherulite calcite growth on the laboratory scale were also included.

## 2.5 | Terminology

### 2.5.1 | Abiotic precipitation

Considered here to be calcite products precipitated due to inorganic physico-chemically forced processes with no influence of organic molecules, microbial exopolymeric substances or microbial metabolisms (see Gallagher et al., 2010).

### 2.5.2 | Biotically influenced precipitation

Defined here as calcite products precipitated under the influence of organic molecules, microbial exopolymeric substances or microbial metabolisms (see Gallagher et al., 2010). Biomolecules can mediate in the transformation process between amorphous calcium carbonate phases and crystalline solids such as calcite or aragonite (Addadi et al., 2003; Ma & Feng, 2015).

*Single crystal* refers here to a crystalline solid in which the crystal lattice of the entire sample is continuous and unbroken to the edge of the sample, with no grain boundaries (Meldrum & Cölfen, 2008; Zhou & O'Brien, 2008). In most instances, single crystals are characterised by a regular internal structure with smooth and planar external faces (Meldrum & Cölfen, 2008); however, single crystals with curved surfaces are also formed in nature (e.g. biominerals) where crystals grow in the presence of organic substances (Meldrum & Cölfen, 2008; Young et al., 1999).

*Polycrystal* refers to polycrystalline solids formed of aggregates of numerous grains or elongated crystallites representing the basic crystallographic units (Cölfen & Antonieti, 2008; Imai, 2016). Polycrystals can grow through the random aggregation of small 'crystal building blocks' (Imai, 2016).

*Calcite spherulites* or *Spherulitic calcite* refer here to spherical to dumbbell-shaped calcite solids internally constituted by a clear polycrystalline arrangement. Consequently, calcite spherical solids not showing such internal architecture were not considered in this study.

*Shrubby calcite* is described here as upward bifurcating and dense radiating, fibrous and polycrystalline calcite solids, either microscopic or macroscopic.

*Benthic microbial textures* encompass those microscopic to macroscopic carbonate components that have formed in close spatial association with microbial communities and/or their exopolymers at the water-sediment interface giving rise to static substrates/crusts (e.g. tufa towers, pinnacles, mounds, microbialites).

*Microbialite* or *microbial deposit* refers here to organo-sedimentary macroscopic carbonate deposits that have accreted as a result of a benthic microbial community trapping and binding detrital sediment and/or forming the locus of mineral precipitation sensu Burne and Moore (1987).

# 3 | RESULTS

The hydrochemical and petrographic data from the batch experiments 1–4 are summarised in Figure 2, with the respective crystalline solids illustrated in Figures 3 through 6. The experimental data presented here are compared with the microscale carbonate products and hydrochemical parameters from the studied alkaline, saline lakes and previous experimental works (summarised in Table 1).

## 3.1 | Experiment 1: Low salinity and without organic acids

Mineralisation experiments performed with salinity equivalent to 2.08 g/L NaCl and devoid of organic acids produced calcite spherulite particles with fully spherical external morphologies showing internal fibro-radial and polycrystalline textures (Figures 2 and 3; Table S2). Spherulites appear as individual bodies (up to 30 μm in diameter) sparsely

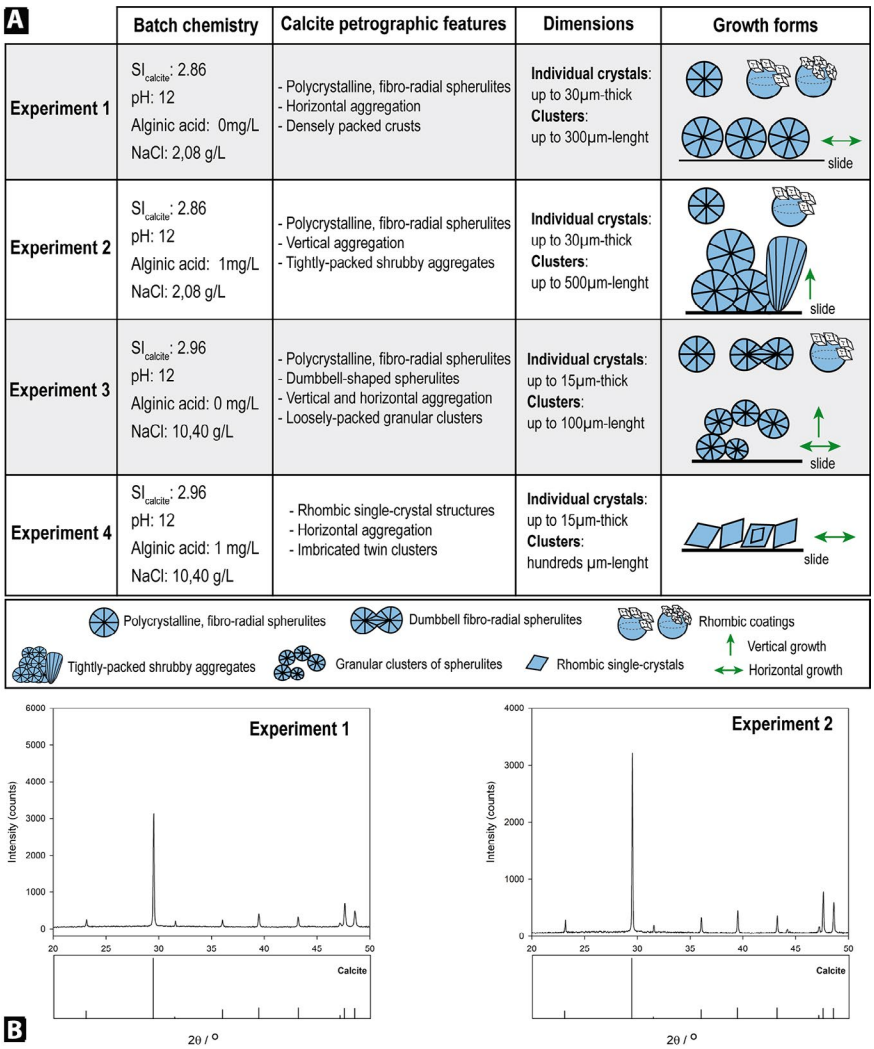


**FIGURE 2** (A) Summary of the hydrochemical and petrographical data from experiments 1 to 4. (B) X-ray powder diffraction data collected from experiments 1 and 2. The lower set of lines indicates the expected peak positions and approximate intensities for a pure sample of calcite

distributed on top of the frosted slides. In some cases, individual spherulites tend to aggregate horizontally until they form densely packed crusts (patches up to 300 µm in length) where spherical outlines can be difficult to clearly identify. Broken spherulites facilitate the observation of a fibro-radial crystalline internal fabric. The spherulite surfaces appear densely covered by an external coating of rhombic crystalline subunits (Figure 3C,D).

The deviation from the typical rhombohedral morphology of calcite can arise from the substantial $Mg^{2+}$ ion contents in the synthetic lake water. In mineralising environments, an increased $Mg^{2+}$: $Ca^{2+}$ ion ratio is known to transiently stabilise amorphous calcium carbonates (Loste et al., 2003; Radha et al., 2012). Following the non-classical pathways of crystallisation, the agglomeration and transformation of amorphous minerals can yield spherulite-like morphologies in $Mg^{2+}$-rich environments (Cölfen & Antonieti, 2008; Huang et al., 2018). The radial crystalline internal fabric (Figure 3D) and surface textures also suggest the involvement of these particle accretion mechanisms, in which crystal growth occurs via the assembly and crystallisation of amorphous particles (De Yoreo et al., 2015; Rodríguez-Navarro et al., 2016).

## 3.2 | Experiment 2: Low salinity and with organic acids

Experiments performed with the identical salinity, but with the addition of 1 mg/L of alginic acid, produced calcite spherulite particles with smoother textures and coalesced forms (Figures 2 and 4; Table S2). Spherulites are present as individual bodies (up to 30 µm in diameter), but laterally linked spherulite habits are much more common and form densely horizontally accreted crusts (in patches up to 500 µm in length) or elongated and tightly packed spherulite aggregations with string-like morphologies (up to 600 µm in length; Figure 4C). Upward and outward aggregation of calcite spherulite bodies was consistently observed giving rise to shrubby tightly packed aggregates with prominent positive reliefs (Figure 4B,D). It is important to note that aggregation of polycrystalline spherulite

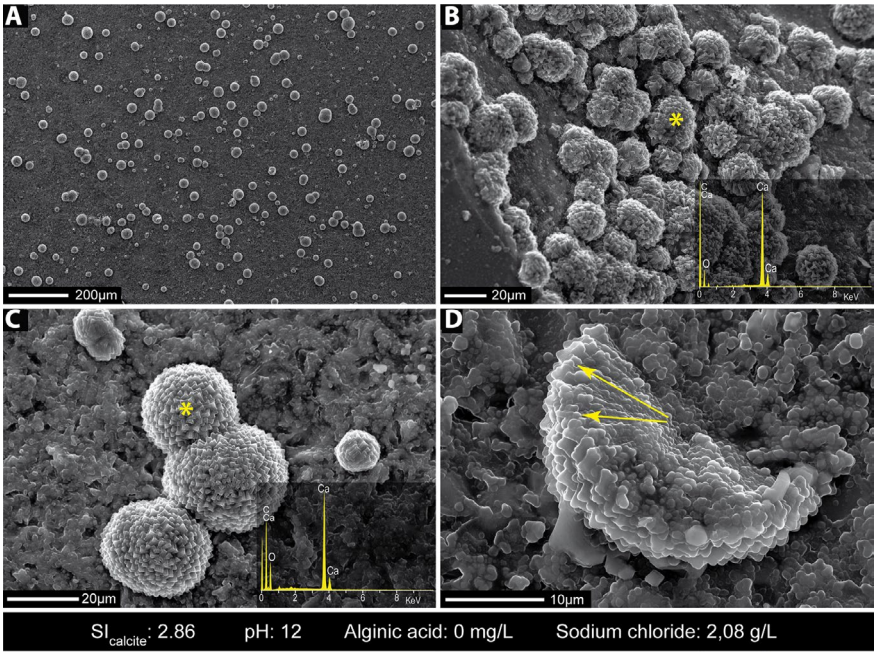


**FIGURE 3** Calcite precipitates from experiment 1 (Alginic acid: 0 mg/L, NaCl: 2.08 g/L). (A) Generalised view of the frosted slide covered by calcite spherules. (B) Clusters of polycrystalline calcite spherulites aggregating horizontally. (C) The external outlines of the spherulites are densely covered by a coating of calcite rhombs. (D) Broken spherulites facilitate the observation of a fibro-radial crystalline internal texture (arrows). Yellow asterisks indicate EDS spot analysis measurement points

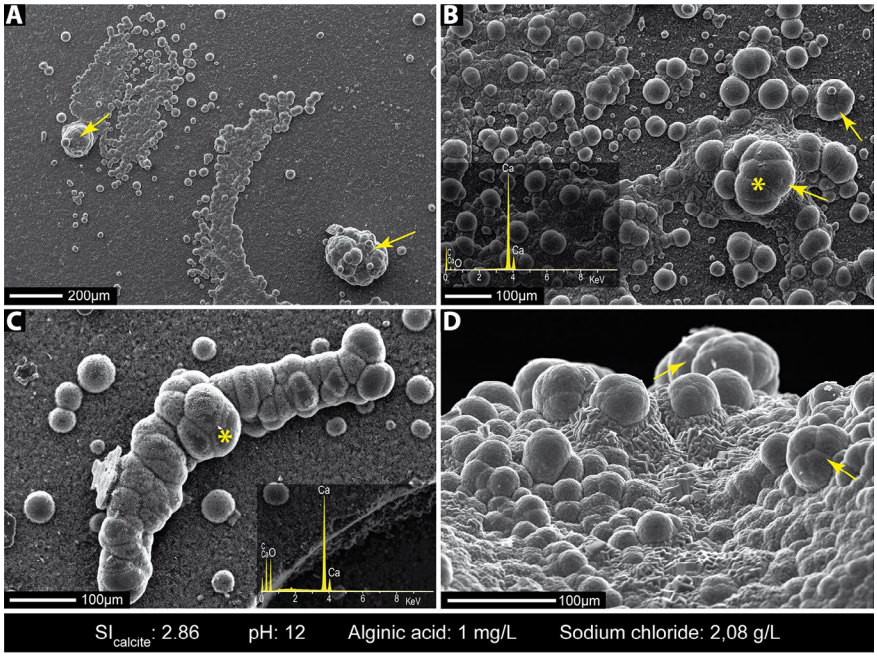


**FIGURE 4** Calcite precipitates from experiment 2 (Alginic acid: 1 mg/L, NaCl: 2.08 g/L). (A) Calcite coverage is localised in specific areas of the frosted slides showing distinct upward and outward aggregation (arrows). (B) Calcite spherulite bodies give rise to shrubby tightly packed aggregates with prominent positive reliefs (arrows). (C) Detail of tightly packed spherulite aggregations forming string-like structures. (D) Lateral view showing aggregation of polycrystalline spherulite bodies producing densely fused, upwards growing crystal solids (arrows). Yellow asterisks indicate EDS spot analysis measurement points

bodies produces densely fused crystal solids rather than a simple cluster of spherules (Figure 4). These observations indicate the roles of acidic macromolecules in controlling not only mineral morphogenesis, but also early formative processes in nucleation and crystallisation.

Previous studies show that alginic acid can inhibit nucleation of mineral particles by sequestering $Ca^{2+}$ ions and also, at elevated pH, by the stabilisation of $Ca^{2+}$ and $CO_3^{2-}$ ion clusters (Rao et al., 2016). Concurrently, the complexation of $Ca^{2+}$ ions to the G units can lead to the self-association of alginate molecules following the 'egg-box' model (Fang et al., 2007). At the onset of particle nucleation, mineral precipitation can occur within the organo-metal matrix, that is, the alginate-$Ca^{2+}$-$CO_3^{2-}$ supramolecular assembly. Such mechanisms might yield aggregates of calcite spherulite bodies (Figure 4C,D). Moreover, the presence of localised mineral layers (Figure 4A) indicates the contributions of polymer-induced liquid-precursor processes, in which liquid phase mineral precursors are transiently stabilised by acidic macromolecules (Gower & Odom, 2000). Thus, in alkaline lake waters, solute state interactions between organic acids and mineral precursors can set the stage for the morphogenesis of aggregated and densely packed polycrystalline spherulites.

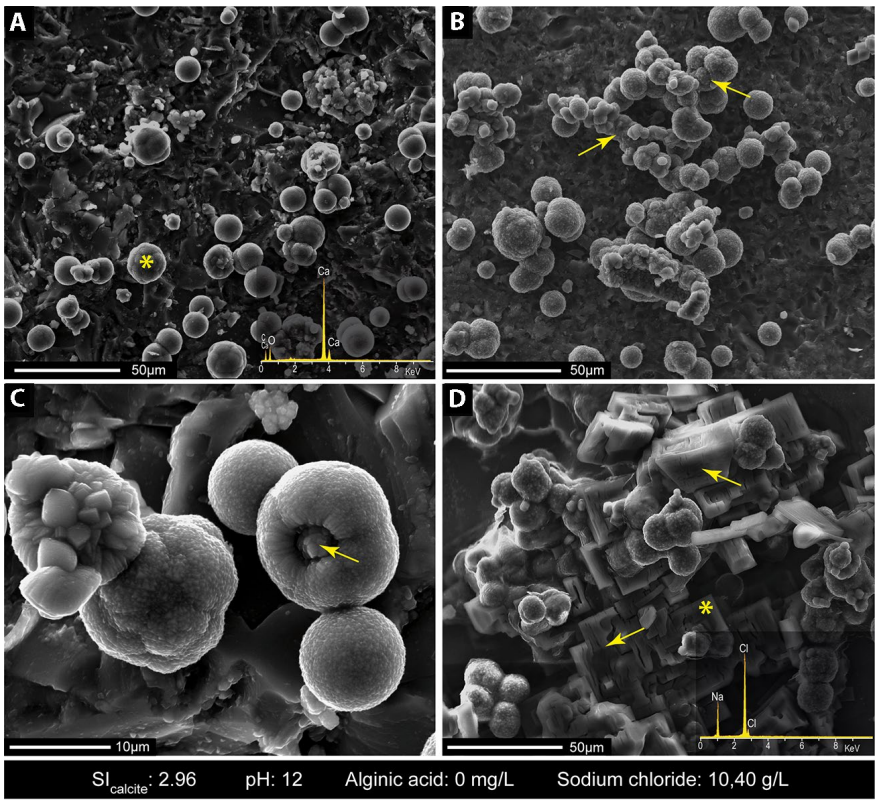


**FIGURE 5** Calcite precipitates from experiment 3 (Alginic acid: 0 mg/L, NaCl: 10.40 g/L). (A) Generalised view showing a reduction of calcite spherulite slide coverage and diameters. (B) Calcite forming granular, arborescent clusters of loosely packed spherulitic bodies (arrows). (C) Both spherical and dumbbell-shaped calcite spherulites coexist (arrow). (D) Halite cubic single crystals are commonly intermingled between calcite crystals (arrows). Yellow asterisks indicate EDS spot analysis measurement points.

## 3.3 | Experiment 3: High salinity and without organic acids

Mineralisation experiments with salinities of 10.40 g/L NaCl and lacking organic acids produced spherulites showing internal fibro-radial and polycrystalline textures (Figures 2 and 5; Table S2). However, spherulite individual bodies (up to 15 µm in diameter) displayed both spherical and dumbbell-shaped morphologies. Bunches of well-defined calcite spherulites are seen forming granular clusters reaching up to 100 µm thick arborescent bodies with positive reliefs (Figure 5B). In this case, aggregation of polycrystalline spherulites produces loosely packed bodies rather than fused structures allowing individual spherules to be easily recognised (Figure 5). In addition, halite cubic single crystals (up to 50 µm in thickness) appeared intermingled between calcites (Figure 5D).

In comparison to the spherulites produced in low salinity experiments (Figure 3), high salinity environments appear to generate smaller particles, but not shrubby calcite. This emergence of smaller mineral particles at extreme salinity could be due to, first, faster nucleation rates on account of a decreased water-$CaCO_3$ interfacial energy with increasing ionic strength assuming the classical nucleation model (Li et al., 2019). However, it is also established that the pathways of $CaCO_3$ nucleation involve ion pairs, pre-nucleation clusters, liquid condensed phases and amorphous precursors (De Yoreo et al., 2015; Gebauer, 2018; Rodríguez-Navarro et al., 2016). In this respect, the occurrence of smaller particle size distributions is explained by the poor association of $Ca^{2+}$ and $CO_3^{2-}$ units prior to mineral nucleation at high salinity, for instance within pre-nucleation clusters and liquid condensed phases (Kellermeier et al., 2014. Here, high salinity conditions could support the existence of several minuscule, phase-separated nano-droplet precursors prior to mineral nucleation, thereby producing not only smaller mineral particles but also less rhombic surface coating (i.e. smoother textures) of the spherulites as morphological vestiges of the formative pathway.

## 3.4 | Experiment 4: High salinity and with organic acids

Mineralisation reactions in the presence of 10.40 g/L NaCl and 1 g/L of alginic acid produced subhedral to euhedral rhombic calcite crystals (up to 15 µm thick) showing smooth edges and, in some cases, displaying imbricated twin clusters up to 10 µm thick (Figures 2 and 6; Table S2). Calcites can be grouped in elongated strips hundreds of microns in length. Moreover, single crystals of cubic halite (up to 10 µm thick) were found imbricated between these carbonates. The total absence of upward growing arborescent habits is a common feature of these mineral assemblages (Figure 6).

An interesting observation is the formation of the thermodynamically favoured rhombohedral crystals of calcite at elevated salinity and alginic acid contents. From a

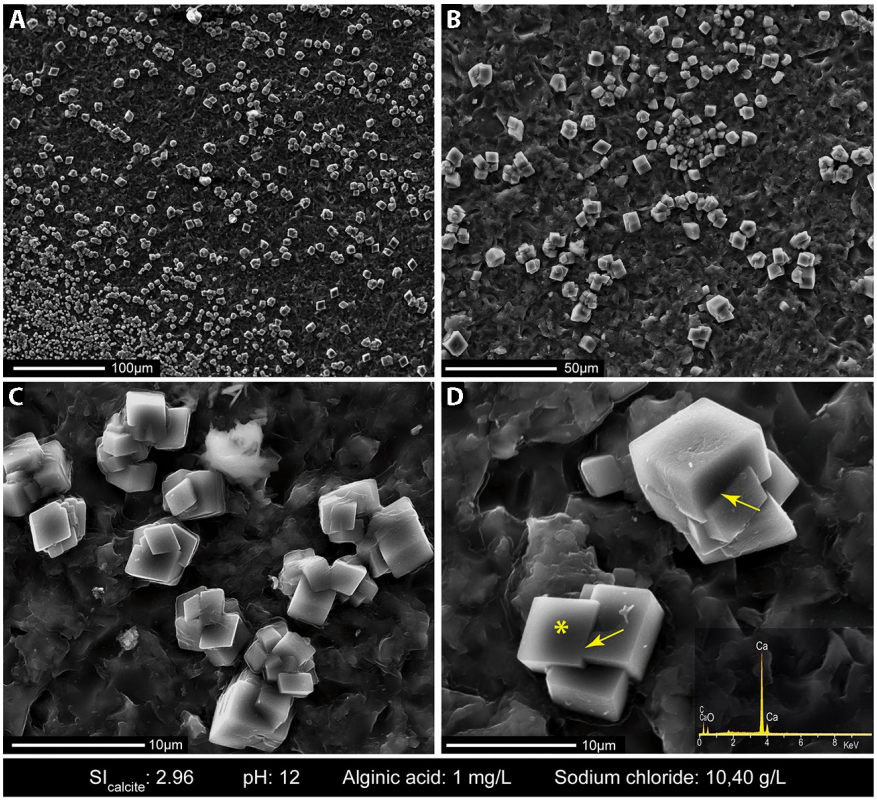


**FIGURE 6** Calcite precipitates from experiment 4 (Alginic acid: 1 mg/L, NaCl: 10.40 g/L). (A) Generalised view of tiny rhombic euhedral calcite crystals covering the slides in elongated strips. (B) Rhombic crystals (up to 15 µm thick) showing smooth edges. (C) Detail of rhombic crystals showing imbricated twin clusters. (D) Detail of imbricated twin clusters in C (arrows). Yellow asterisks indicate EDS spot analysis measurement points

mechanistic viewpoint, the influence of ionic strength alone on the solubility and conformation of alginic acid requires some consideration. For instance, the salting-out of alginic acid by increasing salt contents can deplete the macromolecular solutes (Rehm, 2009), which otherwise might interact with mineral precursors and regulate crystal growth. Here it is possible to show that the applied contents of background salts are critical in modulating the impacts of macromolecules on crystal formation. Increased salinity in the presence of alginic acid produces a switch from polycrystalline spherulite bodies (Figure 4) to euhedral morphologies (Figure 6). Furthermore, the presence of $Mg^{2+}$ ions has previously been shown to mitigate the adsorption of alginic acids to carbonate surfaces (Browning et al., 2020). With the substantial effects of 'background' salts on the nucleation, growth and morphology of mineral particles (Burgos-Cara et al., 2017), chemical gradients associated with even simple monovalent ions might critically modulate the interactions between organic acid and mineral precursors and serve as a key determining factor for mineral form and structure in alkaline lake waters.

## 3.5 | Hydrochemical considerations

Table S2 shows the hydrochemical data, average calcium and magnesium consumption rates and mineralogies reported in experiments 1–4. A striking difference between the average calcium consumption in low saline (2.08 g/L of NaCl; experiments 1 and 2) and high saline (10.40 g/L of NaCl; experiments 3 and 4) reactions over 3 days is observed (Figure 7). While experiments 1 and 2 consumed about 99.76% and 99.66%, respectively, of the initial $Ca^{2+}$ ion contents present in the flasks, experiments 3 and 4 exhausted 96.54% and 88.60%, respectively, of the net $Ca^{2+}$ ions. Within this parameter space, high salinity appears to kinetically promote mineral nucleation, whereas the presence of alginic acid appears to inhibit mineral precipitation. Given that the *p*Ka of carboxylate groups in the sugar residues of alginate chains is about 3.5 (Donati & Paoletti, 2009), a fraction of $Ca^{2+}$ ions sequestered by the carboxylate groups can affect the overall saturation. However, it is also important to consider the association of alginic acid with mineral precursors such as cluster species, liquid condensed phases and amorphous phases, which can produce an inhibitory activity towards mineral nucleation (Rao et al., 2016; Sebastiani et al., 2017). Experiments with organic acids appear to consume less $Ca^{2+}$ ions than experiments without organics acids, with run 4 (high salinity and high alginic acid content) recording the minimum calcium depletion rates (Figure 7). Standard sample preparation for such chemical analyses involves filtration steps using sub-micron pores (typically 0.2 µm) which might have compromised the filtration efficiency of the alginic acid-ion complexes. As such, the estimated metal ion contents not only represent free ion species but also organic acid-bound metal ion species. The presence of (>0.2 µm) soluble organo-calcium complexes as well as the inhibitory effects of alginic acids towards mineral nucleation can explain the low fractions of $Ca^{2+}$ ions consumed in alginic acid-containing mineralisation reactions.

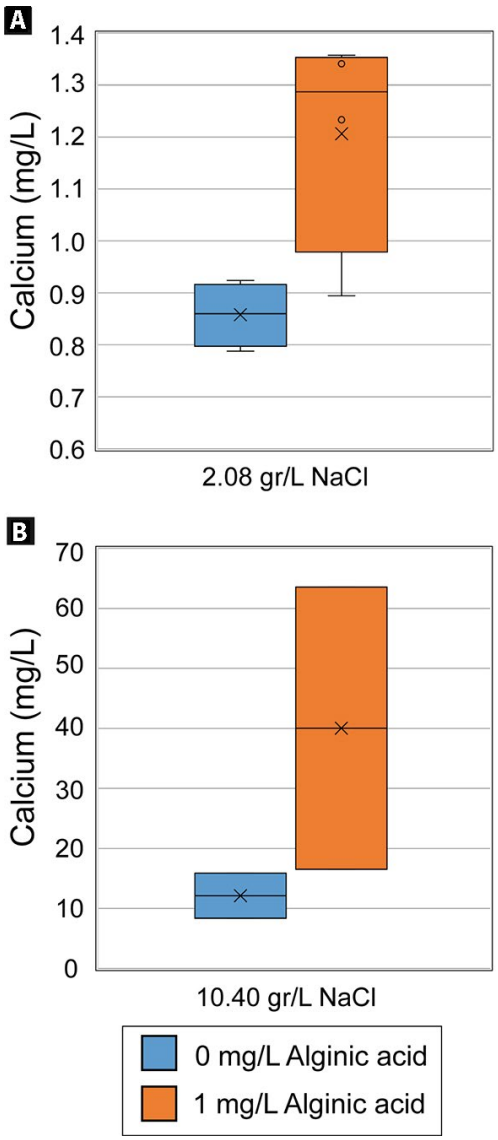


**FIGURE 7** Calcium concentration ($n = 4$) after experiment termination. (A) Low salinity experiment (2.08 g/L NaCl). (B) High salinity experiment (10.40 g/L NaCl)

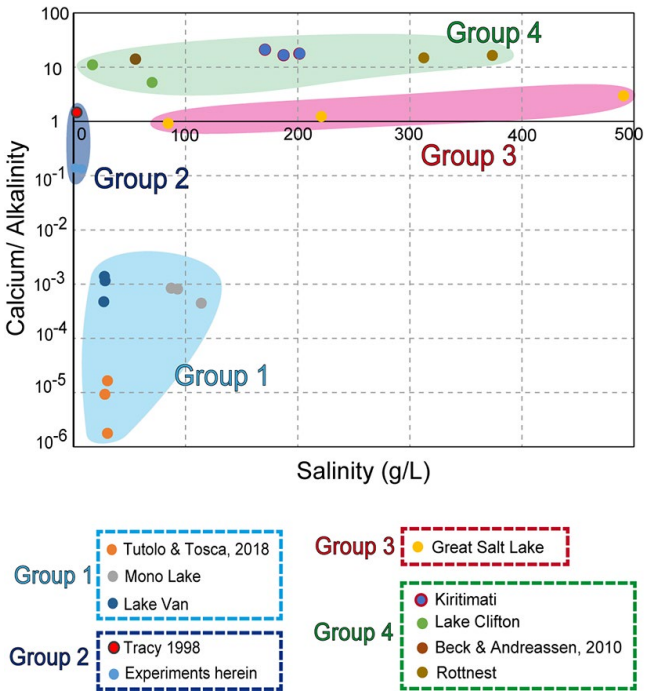


**FIGURE 8** Hydrochemical data from saline lacustrine settings and experiments examined in this work. Logarithmic plot of salinity versus calcium/alkalinity showing the hydrochemical categories in this work (Groups 1–4). See legend and Table 1 for more details

Indicative of the buffering effects of borate species, the pH changes during mineralisation are minor (increase from 12 to about 12.5) and the [Calcium]/[Alkalinity] ratios range between 0.134 and 0.138. All the experiments showed initial Mg/Si ratios of 9.061 and final values of 0 (Table S2). Moreover, saline experiments (1 and 2) recorded slightly lower initial SI calcite values (2.86) than the highly saline experiments 3 and 4 (2.96) estimated with PHREEQC.

## 3.6 | Linking hydrochemistry with petrogenesis in Recent saline lakes and experiments

In view of the water compositions of saline lakes and laboratory experiments conducted in this work, four hydrochemical groups were identified on the basis of degree of salinity and [Calcium]/[Alkalinity] ratios (Groups 1–4 in Figure 8; Table 1). In natural settings, two main types of primary carbonate products have been documented: (a) biofilm-free sediments, normally formed as water column single-crystal micro-precipitates, and (b) mounds or microbialites originated as benthic microbial accumulations made up of more diverse micro-crystal calcite assemblages (Figure 9; Table 1). The twofold distinction is rather artificial as several constructive and destructive processes may have played in tandem leading to evolved forms (Ge et al., 2020). However, this classification is based on: (a) micro-crystal precipitate morphology, and (b) location of authigenic precipitation (water column vs. benthic).

### 3.6.1 | Group 1. Low [Ca]/[Alk] ratios and low salinities

This group includes Mono Lake (USA) and Lake Van (Turkey), endorheic, saline lakes which are characterised by the highest alkalinity values (between 151 and 630 mEq/L) and calcium concentrations between 0.074 and 0.514 mEq/L (Figure 8; Table 1). The [Ca]/[Alk] ratios fluctuate between $4 \times 10^{-4}$ and $1 \times 10^{-3}$ while salinity values fall between 26 and 114 g/L. Loose carbonate particles consist of micron-sized calcite and aragonite flakes, and carbonaceous clayey silt. Carbonate microfabrics are

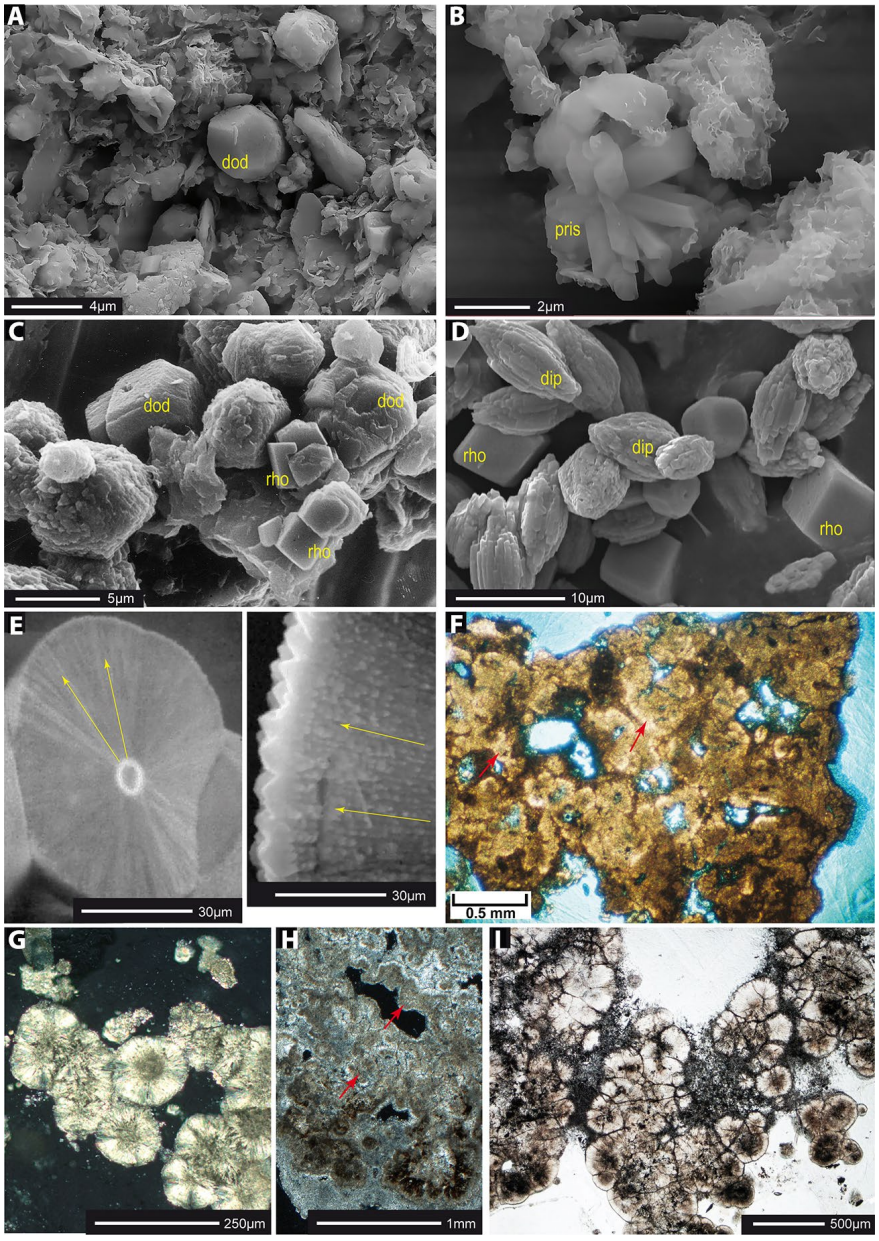


**FIGURE 9** SEM and thin-section photomicrographs of calcite petrographies from natural lacustrine sites and experiments from Groups 1 to 4. (A, B) Carbonate microfabrics represented by aragonite dodecahedron-like calcite single crystals (dod), and prismatic aggregated needles (pris) formed in the water column of Lake Van (Courtesy J. McCormack). (C) Water column micritic calcite precipitates showing dodecahedron-like calcite single crystal morphologies (dod) in Pyramid Lake, USA (courtesy G. Arp). (D) An assemblage of protruded dipyramid (dip) and rhombic calcite single crystals (rho) formed in abiotic experimental runs (courtesy B. Tutolo). (E) Calcite spherulites with fibro-radial growths (arrows) from experimental runs (left) (from Tracy et al., 1998a). Note that fibres (arrows) are densely covered by a coating of single rhombic calcite crystals (right image) (courtesy S. Tracy). (F) Great Salt Lake (USA) Recent pustular microbial mats locally show a 'lumpy' texture composed of spherulitic calcite structures formed in the lake mixing zone (arrows) (courtesy T. Chidsey). (G) Microbial mat-related spherulites growing in hypersaline to fresh lagoons in Kiritimati (Central Pacific) (courtesy G. Arp). (H) Clotted peloidal micrite and sinuous threads forming subspherical structures of micrite to fibrous crystal cementstone (arrows) from Mono Lake spring pinnacles (courtesy G. Della Porta). (I) Cluster of calcite spherulites formed in association with microbial communities (microbialites) at Rottnest hypersaline lagoons (Australia) (courtesy K. Bischoff)

represented by aragonite needles and dodecahedron-like calcite single crystals (Figure 9A,B) which resemble the micritic calcite precipitates found in other saline soda lakes from the USA Great Basin (Pyramid Lake, Figure 9C). Moreover, large microbialite chimneys are made up of homogenous clotted aragonitic to finely laminated low-Mg calcite microfabric and also groups of spheroidal bodies constituted by alternating dark and light concentric aragonitic to low-Mg calcite layers (Kempe et al., 1991; López-García et al., 2005).

Contemporaneous to Holocene Mono Lake carbonate sediments are dominated by a fine silt fraction of allochthonous tufa-rich sands and aragonite flake muds, representing about 7% of the total sediment volume in the first metres of the lake column (Newton, 1994). Furthermore, Mono Lake towers are constituted by an array of distinct microfabrics including leiolitic, clotted peloidal micrite, clotted microcolumnar and sinuous rims of micrite/microsparite, the outermost Recent parts being mostly dominated by clotted peloidal micrite of microbial origin (Brasier et al., 2018; Della Porta, 2015).

Regarding the laboratory examples, the experiments by Tutolo and Tosca (2018) were designed with alkalinity and calcium concentrations broadly falling within the Mono Lake and Lake Van natural counterparts, with [Ca]/[Alk] values oscillating between $1 \times 10^{-5}$ and $2 \times 10^{-6}$, and salinity values between 27 and 30 g/L. In general, these abiotic calcite precipitating runs produced an assemblage of dodecahedron-like, elongated dipyramid, protruded dipyramid and rhombic calcite single crystals (Figure 9D).

### 3.6.2 | Group 2. Moderate [Ca]/[Alk] ratios and lower salinities

This group includes the experimental data presented here and the observations of Tracy et al. (1998a, 1998b) regarding the growth of calcite spherulites from abiotic solutions. In both experimental datasets, alkalinity values are relatively high, between 14 and 131 mEq/L and calcium concentrations between 17 and 100 mEq/L. In addition, [Ca]/[Alk] ratios fluctuate between 0.138 and 2.72 while salinity values fall between 0.7 and 10.40 g/L (Figure 8; Table 1). In this group, calcite spherulite grains display a clear polycrystalline, fibro-radial arrangement with grain diameters oscillating between 20 and 60 μm (Figure 9E).

### 3.6.3 | Group 3. Moderate [Ca]/[Alk] ratios and higher salinities

This hydrochemical group is represented by the Great Salt Lake: a hypersaline, endorheic lake. Alkalinity values are moderate, between 5.35 and 8.4 mEq/L, and calcium concentrations are similar, between 6 and 16 mEq/L. This enables [Ca]/[Alk] ratios to fluctuate between 0.9 and 3, while salinity concentrations show a remarkable variability between 84 and 490 g/L (Figure 8; Table 1). Contemporaneous Great Salt Lake sediments consist of muds, ooids, oncoids and bioherms/ microbial deposits (Chidsey et al., 2015; Della Porta, 2015; Vennin et al., 2019). Despite muds being volumetrically the most abundant sediment type, their calcium carbonate portion is thought to have been transported as wind or river particles to the lake (Bouton et al., 2019; Eardley, 1938). The microfabrics of the carbonate bioherms/microbialites consist of a leiolitic to clotted peloidal micrite/microsparite hosting micritic laminae, peloids and coccoid components (Della Porta, 2015; Vennin et al., 2019). In addition, recently forming pustular microbial mats locally show a 'lumpy' or 'bumpy' texture composed of well-defined spherulitic calcite structures (Chidsey et al., 2015; Figure 9F).

### 3.6.4 | Group 4. Higher [Ca]/[Alk] ratios and moderate-high salinities

This group encompass the fresh to hypersaline Kiritimati atoll lakes (Central Pacific), hypersaline island lakes (Australia) and Lake Clifton coastal hyposaline lagoons (Australia). In this group, alkalinity values represent the lowest of the dataset, fluctuating between 1.71 and 4.25 mEq/L, and having a range of calcium concentrations between 13.6 and 530 mEq/L (Figure 8; Table 1). In addition, the resultant [Ca]/[Alk] ratios shift between 5.2 and 76.8, while salinity contents can vary between 16.8 and 373 g/L. Carbonate products documented in these natural settings include micrite muds, peloids, microbialite/skeletal sands, thrombolite mounds and microbial mat-related spherulites (Figure 9G) to spherulitic microbialites (Figure 9I; Arp et al., 2012; Bischoff et al., 2020; Burne & Moore, 1987; Burne et al., 2014; Moore, 1993).

In addition, experimental calcite precipitates falling within this hydrochemical group display alkalinity values of 37 mEq/L, elevated calcium concentrations of 530 mEq/L, [Ca]/[Alk] ratios of 14 and salinity concentrations of 53.8 g/L. In these batch experiments, the obtained polycrystalline calcite spherules reached 20 μm in diameter (Beck & Andreassen, 2010, their fig. 25).

## 4 | DISCUSSION

### 4.1 | Single-crystals versus polycrystals: Calcite crystal growth

This work shows that salinity, organic acid contents and alkalinity are key factors regulating the morphology and textural diversity of non-enzymatic carbonates as spherulites, agglomerates and rhombohedra. From the viewpoint of crystal growth, abiotic experiments with alkaline saline waters can precipitate abundant fibro-radial polycrystalline calcite spherulites. The elevated SI of the solutions (between 2.86 and 2.96), as well as the slow but gradual solvent evaporation are the driving forces for crystal formation and growth. Rather than the typical rhombohedral (equilibrium Wulff) form of calcite, spherulite morphologies are observed (experiments 1–3). This morphogenesis is guided by the heterogeneous ionic compositions of the growth media, containing

a $Mg^{2+}$:$Ca^{2+}$ ratio of about 1 in these experiments. High $Mg^{2+}$ ion contents can produce polycrystalline calcite particles even with simple fluid compositions (Loste et al., 2003; Reddy & Nancollas, 1976) and affect mineralisation pathways at distinct steps by (a) interacting with ion clusters (Wolf et al., 2015), and (b) regulating the water contents and stability of mineral precursors (Du et al., 2020; Huang et al., 2018). Further exploration of this parameter space will help generate a more robust correlation of the textural transitions of minerals in lake waters with complex fluid compositions and also elucidate the roles of chemical (inorganic and organic) gradients in petrographic diversity of calcites.

Considering the roles of salinity, an increase in NaCl contents produces smaller calcite spherulites with smoother textures. This observation is attributed to either lower water-$CaCO_3$ interfacial energies, which can yield several nucleation events with a short time span, or poor ion association at elevated salinity providing several mineral precursor droplets prior to nucleation. On the other hand, the introduction of alginic acids produces key modifications in crystal morphogenesis (Figure 10). Moderate contents of the organic acid (1 mg/L) lead to tightly packed spherulite aggregates. This organisation suggests that mineral precipitation occurs in association with an organic matrix rather than the post-mineralisation stacking of spherulites. This phenomenon is also supported by the decreased solubility of alginates in the presence of $Ca^{2+}$ and $Mg^{2+}$ ions (Haug & Smidsrød, 1965). Thus, with moderate contents of the biopolymer, the nucleation and growth of mineral particles occurs within an organo-metal matrix (alginate-$Ca^{2+}$-$CO_3^{2-}$ assembly), nonetheless retaining the effects of the (smaller) ionic species such as $Mg^{2+}$ towards spherulite growth. With identical alginic acid contents but increased salinity (from 2.08 to 10.40 g/L), the mineralisation reactions produce prominent rhombohedral crystals of calcite (Figure 10A). This transition is attributed to the precipitation of alginic acids as calcium or magnesium salts under high salinity conditions (Charfi et al., 2017; Haug & Smidsrød, 1965). Such precipitation events deplete not only the organic acids but also divalent $Ca^{2+}$ and $Mg^{2+}$ ions from solution which otherwise mediate spherulite formation. In summary, in abiogenic waters, inorganic species such as $Mg^{2+}$ affect mineral morphology and structure in a pH-dependent manner and salinity-dependent manner. However, in the same environment, biopolymers affect mineralisation in a concentration-dependent manner with indications of 'non-monotonicity'. Such 'non-monotonic' relationships between (a) net contents of ionic and organic molecules (additives) in mineralisation media and (b) emergent crystal morphologies and structures arise from inter-additive interactions transpiring concurrent to mineral nucleation and growth. Such observations illustrate these complex relationships by identifying the dual roles of salinity on mineralisation in natural environments: first, in regulating the kinetics associated with nucleation, phase transformation and crystal growth and second, in modulating the availability (i.e. solubility) and depletion (i.e. precipitation) of ionic and organic species that regulate mineral morphogenesis.

## 4.2 | Relationships between hydrochemistry and petrography in saline lacustrine carbonates

Sediments constituted by authigenic polycrystalline spherulites are remarkably rare in Recent saline lacustrine environments,

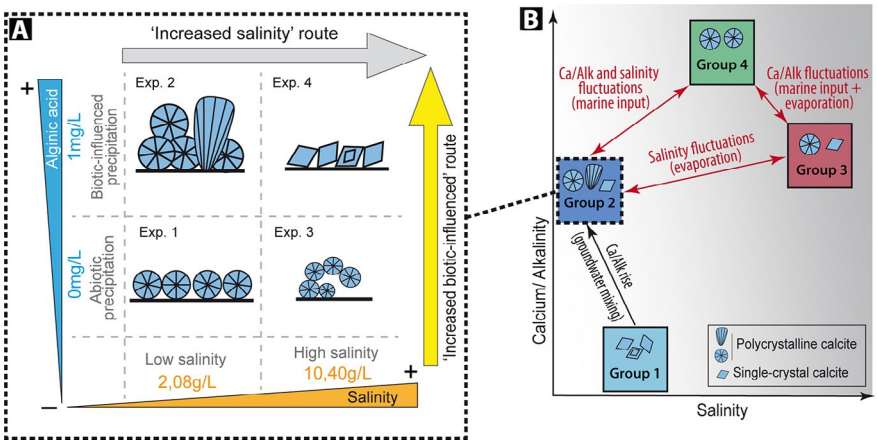


**FIGURE 10** (A) Summary of hydrochemical conditions giving rise to calcite petrographical features from experiments 1–4 herein. Polycrystalline and upward growing calcite aggregates can be better explained where abundant alginic acid concentrations coexist with high (Calcium)/(Alkalinity) waters (acronym: [Ca/Alk]). See Figure 2 for details. (B) Conceptual scheme illustrating the hydrochemical groups according to [Ca/Alk] ratios and salinities. Red double-arrowed lines refer to probable routes between hydrochemical Groups 2–4 in which calcite spherulite formation has been commonly recognised. The black arrow represents mixing of calcium-rich groundwaters (Group 2) with soda lake waters (Group 1) producing enhanced [Ca/Alk] waters that can lead to localised formation of calcite spherulites

where mud-size single crystals are volumetrically much more common. Some lacustrine evaporitic settings such as the Great Salt Lake, Kiritimati and Rottnest lagoons represent exquisite exceptions recording exotic Recent calcite spherulite sediments clearly occurring in association with microbial mat-related structures or their exopolymers in highly saline settings (Arp et al., 2012; Bischoff et al., 2020; Chafetz et al., 2018; Chidsey et al., 2015; Kirkham & Tucker, 2018).

Lake waters where Recent spherulite carbonates are formed (Groups 3 and 4) tend to have moderate to high [Ca]/[Alk] ratios (Figure 8; Table 1). Even though waters in Groups 3 and 4 are characterised by a range of saline to hypersaline values (between 16 and 490 g/L), spherulitic calcite all occurs as spherules rather than tightly packed vertically oriented shrubby aggregates such as those described in the Pre-Salt examples (Figure 1A,B; Gomes et al., 2020).

Group 2 shows a range of experimentally produced calcite spherulites and shrubby aggregates arising from solutions having moderate [Ca]/[Alk] ratios and remarkably low NaCl contents (between 0.7 and 10.40 g/L; Figures 3, 4, 8 and 9E; Table 1). Thus, it seems that fluctuations in salinity due to evaporation concentration (Great Salt Lake) or mixing with marine waters (Kiritimati or Rottnest lagoons) are not causatively related to the formation of calcite spherulites, or even the intermediate morphologies between spherulitic and shrubby calcite. The diameters of experimentally produced calcite spherulite clusters (up to 300 μm) and shrubby aggregates (up to 500 μm) are smaller than the allochems documented in the Pre-Salt assemblages or contemporaneous saline lakes (Figures 1A, B and 9). This fact probably reflects that the experiments contained a reduced mass of calcium and magnesium which was quickly consumed due to fast rates of calcite precipitation (Figure 7) limiting the dimensions of the particles. Therefore, size differences between Recent and ancient lake allochems and experimental grains are probably responding to a scaling issue.

The abiotic experiments 1 and 3 described here allow the effects of small salinity variations in calcite morphology and precipitation rates to be examined (Figure 10A). In other words, it is possible to evaluate the impact that salinity fluctuations—likely occurring in evaporitic contexts—have on crystal shape. The [Ca]/[Alk] ratios in experiments 1 and 3 broadly fall within the ranges encouraging polycrystalline calcite in the preceding experiments (Tracy et al., 1998a, 1998b). Also, slight salinity increments from 2.08 to 10.40 g/L in abiotic conditions did not encourage shrubby calcite, but rather reduced the size of the spherules from 30 to 15 μm (Figures 2, 3, 5 and 10A), and the calcite precipitation rate. The reduction in spherule size seems to run in parallel to the increase in salinity (ionic strength, Table S2) (experiment 3; Figure 7) which lowers the calcium removal rates of the solution.

Wider salinity values (between 16 and 490 g/L) recorded in lakes from Groups 3 and 4 (Figure 8; Table 1) do not seem to prevent the formation of spherulitic textures when they occur in association with microbial mats and their organic exopolymers (Arp et al., 2012; Bischoff et al., 2020; Chidsey et al., 2015). However, the observation that enhanced salinity and rising microbial organic contents (experiment 4 herein, Figure 10A) preclude the formation of synthetic polycrystalline calcite—actually promoting calcite single-crystals—disagrees with the observation of spherulites forming in saline and microbial-rich lakes of Groups 3 and 4 (Figures 9F–H and 10B).

This observation suggests that the inhibitory effect of increased salinity could have been offset by the potential biofilm metabolic effects increasing the pH and calcite saturation to promote spherulite calcification (Arp et al., 1999, 2012; Bischoff et al., 2020; Gallagher et al., 2010; Mercedes-Martín et al., 2017; Figure 10B). Thus, despite bulk environmental perturbations, the presence of biofilms or their biopolymers could have helped to maintain nearly constant SI values in the surrounding microbial ecospace facilitating biotically influenced spherulite formation (sensu Bissett et al., 2008).

The combination of extremely low [Ca]/[Alk] ratios and higher alkalinities in Group 1 soda lakes is expected to preclude the abiotic formation of polycrystalline calcite in the lake waters as demonstrated by the type of sediments recognised in the first centimetres of Mono Lake beds (Newton, 1994), Lake Van (McCormack et al., 2019; Stockhecke et al., 2014) and Pyramid Lake (Arp et al., 1999; Reddy & Hoch, 2012; Figure 9A–C). These authigenic sediments are dominated by micron-sized aragonitic muds showing single crystal rhombic to prismatic morphologies and considered as water column abiotic precipitates formed either as plume whitings in the river-lake mixing zone or due to evaporation-driven supersaturation processes (McCormack et al., 2019; Reddy & Hoch, 2012). Aragonite formation rather than calcite is preferred due to the high Mg/Ca in the lake water (Wang et al., 2012). Even though photosynthetic microbial activity can occur associated with Lake Van water column precipitates this process does not seem to promote spherulitic carbonate morphologies in such lake (see Figure 9A,B). In soda lakes, a minor rise in microbial photosynthesis-induced calcite supersaturation is observed because high alkalinity waters facilitate a large pH buffering (Arp et al., 1999, 2001), and the mineral formation rate will be limited by the very low [Ca]/[Alk] ratios (Wolthers et al., 2012) rendering the formation of calcite spherulites unlikely. A possible exception to this rule would occur in lake locations where calcium-rich groundwater mixes with alkaline lake waters locally increasing the [Ca]/[Alk] ratios of the mixture allowing an extra pumping of calcium enabling extreme calcite supersaturation and more equal [Ca]/[Alk] ratios (Figure 11A). Examples of

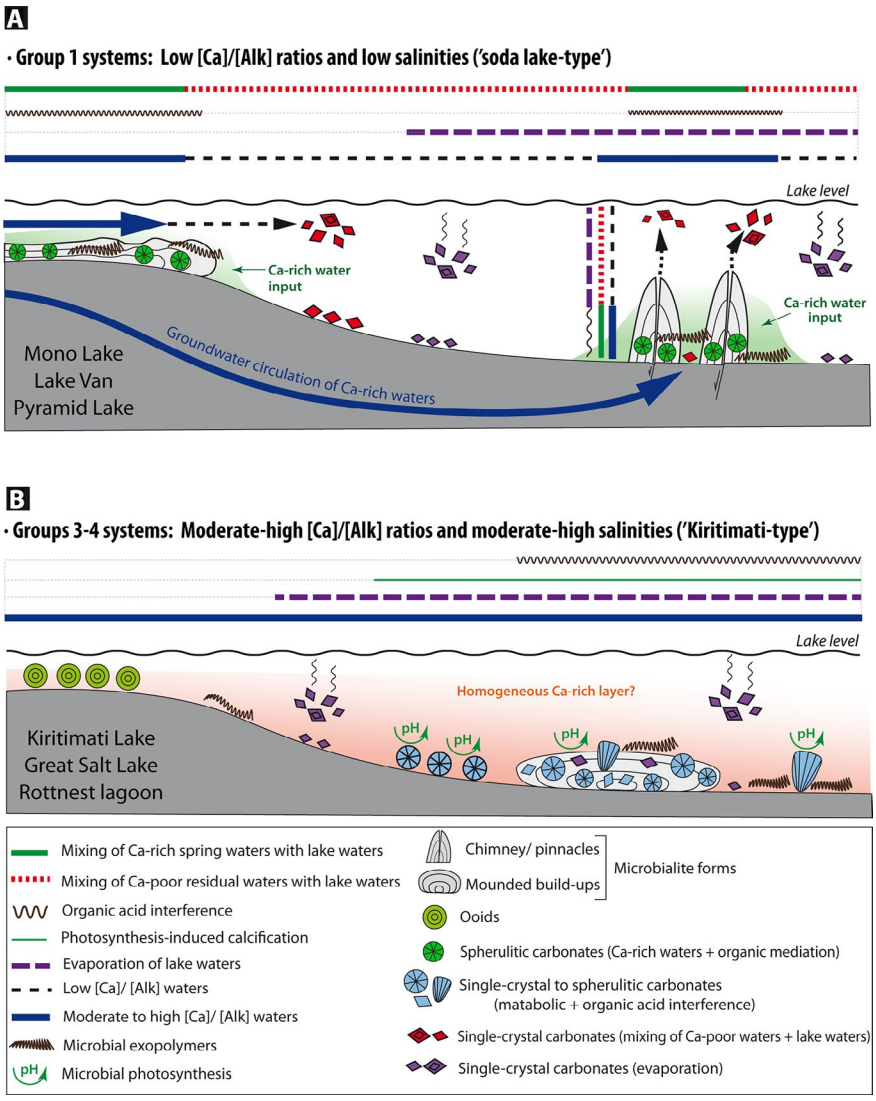


**FIGURE 11** (A,B) Depositional models for Group 1 and Groups 3 and 4 lakes, respectively, summarising the overall processes and carbonate precipitates (water column, loose particles and microbial benthic structures). The colour pattern links processes with carbonate products

calcium carbonate spherulitic grains forming in the mixing zones of alkaline soda lakes occur either in the lake shore of Pyramid Lake (Arp et al., 1999, p. 171), or within Lake Van pinnacles (Kempe et al., 1991, p. 607), and spring-feed tufa towers in Mono Lake (Figure 9H; Della Porta, 2015). Remarkably in these examples, the formation of spherulitic microtextures occurs in close spatial association with benthic microbial mats and their exopolymers rather than in the lake water column as purely abiotic precipitates (Brasier et al., 2018; Kempe et al., 1991). Consequently, the formation of lake floor spherulitic calcite allochems will probably be very localised in soda lakes (Figure 11A).

The preference for waters with low [Ca]/[Alk] ratios and higher alkalinities (Group 1) to produce single crystal abiotic calcite has been also experimentally demonstrated by the formation of dodecahedron-like and elongated to protruded dipyramid and rhombic calcite crystals (Tutolo & Tosca, 2018; Figure 9D) resembling microcrystalline carbonates formed as abiotic whitings in the water column of Pyramid Lake (Arp et al., 1999; compare Figure 9C with D). These observations suggest that calcite spherulites are more likely to occur in saline to hypersaline lake waters with moderate to high [Ca]/[Alk], low alkalinities, and aided by the counteracted effects of microbial metabolism and organic exopolymers (Figure 11B).

A notable exception to this rule seems to be the hyposaline Lake Clifton in Australia. Despite having high [Ca]/[Alk] and low alkalinity waters the thrombolitic deposits of this lake are characterised by the apparent absence of early formed carbonate phases including spherulitic carbonates (Burne et al., 2014).

## 5 | CONCLUSIONS

By combining mineralogical and hydrochemical data from selected evaporitic lacustrine systems and lake water chemistry mimetic mineralisation experiments, the effects of salinity, calcium versus alkalinity, microbial metabolism and organic acids in the formative processes of calcite spherulites and shrubby calcite have been explored. Spherulitic calcite

preferentially forms in saline and/or alkaline waters in lacustrine and laboratory settings with a moderate to high [Ca]/[Alkalinity] ratio rather than in calcium-depleted systems (such as soda lakes). In addition, a causative relationship was not found between evaporative-driven salinity fluctuations (between 1 and 400 g/L of NaCl) and the preferential formation of either calcite spherulites, shrubs or their intermediate morphologies, bringing into question the role of evaporation alone towards spherulitic calcite development. Indeed, the experimental data suggest that salinity increments notably lowered the size of the calcite spherules and did not encourage shrubby calcite under the salinity range studied. This observation highlights the roles of concentration regimes associated with organic and inorganic molecules against the background salinity, conditioned by evaporation concentration, in determining the morphological and growth form transition of minerals. Spherulitic calcite growth did not occur in the presence of organic acids and high salinity implying that such inhibition is probably offset by the potential effects of microbial metabolic processes as recognised in all Recent spherulite-bearing lake systems. Consequently, microbial photosynthesis can raise the pH to levels allowing calcite supersaturation and spherulite mineralisation while organic molecules can impact the kinetics of spherulitic calcite aggregation in waters with moderate to high [Ca]/[Alkalinity] values.

Soda lake waters and experiments with low [Ca]/[Alkalinity] ratios and moderate salinity tend to produce an assemblage of single-crystal precipitates formed abiotically during water column mixing episodes or evaporation. Due to the calcium-limited nature of soda lake systems it is hypothesised that abiotic spherulitic calcite will be rather restricted in the lake water column (or sediment–water interface) as demonstrated by the type of micritic precipitates collected in Lake Van, Mono Lake or Pyramid Lake floors which formed abiotically in the water column. The unusual observation of spherulitic calcite components in Recent saline soda lakes (e.g. Mono Lake or Lake Van) can be explained by the existence of locally enhanced [Ca]/[Alkalinity] ratios occurring in specific lake locations where calcium-rich groundwaters mix with lake waters forming vertical chimneys on the lake floor. The close spatial association of microbial exopolymers with spherulites in these chimneys strongly advocates towards an organic acid control lowering the inhibitory effect of increased salinity, probably favouring spherulitic calcite nucleation.

### Acknowledgements

Special thanks go to the scientists who generously contributed with their own photomicrograph and SEM material to illustrate the crystal assemblages discussed in this work. They include Gernot Arp, Karl Bischoff, Tom Chidsey, Giovanna Della Porta, João Gomes (under Petrobras permission), Jeremy McCormack, Sharon Tracy and Benjamin Tutolo. Carlos Ayora is warmly thanked for stimulating discussions on Lake Chad geochemical modelling (Figure 1). We are grateful to the reviewers for critically reading and reviewing the manuscript, in particular the valuable comments and constructive and detailed criticism of Adrian Immenhauser and Nathan Rochelle-Bates. We also would like to thank Enrico Capezzuoli and Greta Mackenzie for their Editorial assistance. M.S.R. acknowledges financial support from Origin Center, project 190438131, Dutch Research Council (NWO) and Dutch National Science Agenda (NWA).

## CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## DATA AVAILABILITY STATEMENT

The data for this study are shown in the various figures and in tables.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

**How to cite this article:** Mercedes-Martín R, Rao A, Rogerson M, Sánchez-Román M. Effects of salinity, organic acids and alkalinity on the growth of calcite spherulites: Implications for evaporitic lacustrine sedimentation. *Depositional Rec*. 2021;00:1–22. https://doi.org/10.1002/dep2.136